Visualization for Architecture, Engineering, and Construction: Shaping the Future of Our Built World

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***Abstract*—Our built world is one of the most important factors for a livable future, accounting for massive impact on resource and energy use, climate change, but also the social and economic aspects coming with population growth. The architecture, engineering, and construction industry is facing the challenge that it needs to substantially increase its productivity, let alone the quality of the building of the future. In this paper, we discuss these challenges in more detail, focusing on how digitization can facilitate this transformation of the industry, and link them to opportunities for visualization and augmented reality research. We illustrate solution strategies for advanced building systems based on wood and fiber.**

THE INTRODUCTION

Our future built world provides some of the most important challenges on a global scale. We are facing the problem that worldwide population growth and advancing urbanization lead to a massive increase in the demand for housing. Due to population growth and demographic shifts, the architecture, engineering, and construction (AEC) industry faces the challenge of building housing and infrastructure for over 2.5 billion people in urban areas over the next 30 years. The construction, operation, and maintenance will add to the substantial ecological footprint of the building industry, which is a significant contributor to climate change, accounting for over 40% of the global energy use, 50% of global waste, and 30% of global greenhouse gases [1]. Therefore, improvements in AEC promise to have a massive and immediate boost toward improved sustainability and higher quality of our human-made environment.

Increasing digitization and automation is an important cornerstone to achieve this improve-

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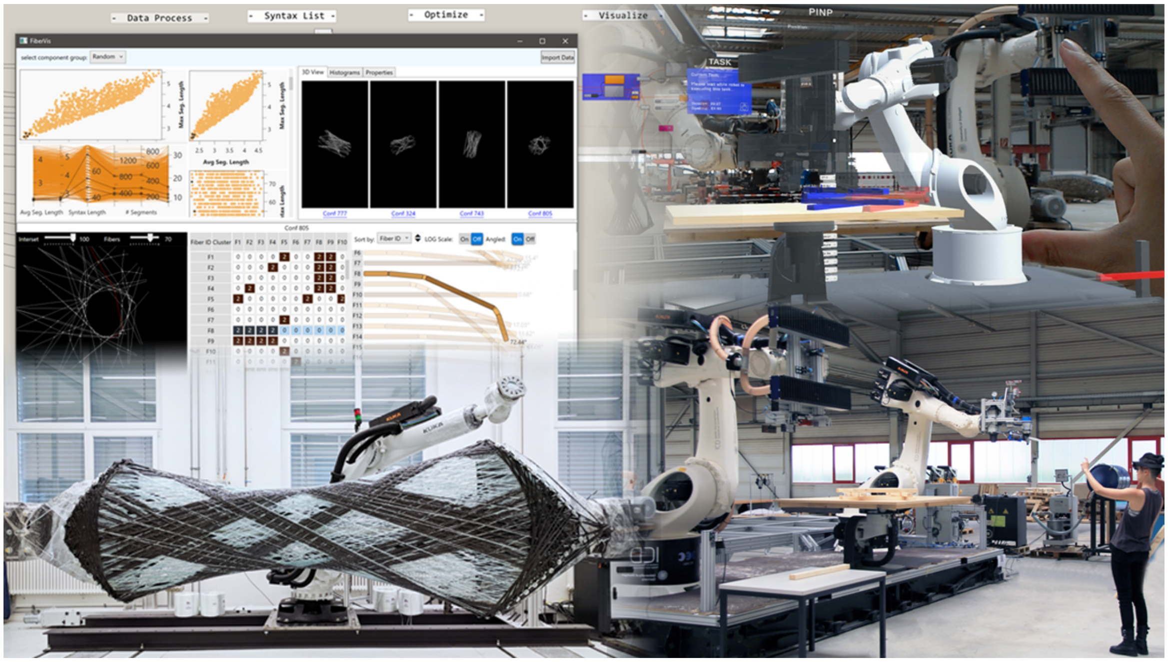

Figure 1: Interactive data visualization (top-left) and immersive technology (right) will be the vehicle to support advanced digital and robotic fabrication and construction (bottom-left). ©ICD/ITKE University of Stuttgart.

ment. Not only does it lead to increased productivity, thus meeting the higher demand for buildings, but it can be leveraged to improve the processes and output of the AEC industry: more resource-saving construction and operation of the built environment and, at the same time, a more livable environment. Unfortunately, today's AEC industry is characterized by a stagnating or even decreasing level of productivity over the last three decades [2]. This is in stark contrast to other industries, such as the automotive industry, which have been benefiting substantially from digitization [3]. However, the concepts employed there cannot be trivially transferred to, and implemented in, the building industry given its demand for predominantly project-based solutions and the difficulties in continuing the digital process chain beyond the prefabrication environment to the construction site.

Therefore, we aim to adopt these technological developments for new methods of digitization in the building industry. A product-based approach toward buildings is often proposed as a strategy to increase productivity growth, but this contradicts the intrinsic qualities, resilience, and flexibility of the trade drastically and is calculated to only provide additional benefits in a niche part of the industry (i.e., ready-made homes). For the grand majority of buildings, a project-based approach is better suited. This approach, in turn, brings up the challenge of flexible automation technologies in AEC and the reuse of machines and technologies across projects. Digital workflows have been partly established—especially in the prefabrication of timber construction—but still do not sufficiently include the processes on the construction site.

Some successful examples of innovative architectural designs are already enabled by advanced digital and robotic fabrication and construction. Figure 2 illustrates some of these already built examples: the Wood and Fiber Pavilions at the German National Garden Festival 2019. These also serve as guiding examples for this paper. We will revisit them and discuss how we can further enhance the planning, fabrication, and construction of these or other future buildings. The previous experiences with such non-traditional buildings are the foundation for identifying the challenges and opportunities for visualization in AEC. Therefore, this paper is based on a collaboration between visualization and augmented reality (AR) experts on the one hand and architects and experts in digital fabrication in building construction on the other hand.

We argue that interactive data visualization and immersive technology will be the vehicle to support the transition of the building industry to a more data-driven and digital environment (see Figure 1). The increasing amount and diversity of data produced by the AEC industry call for tools that can handle that data and allow practitioners to incorporate it into new, more effective, and more efficient processes. Many design studies in visualization research have shown how visualization tools can enable exactly that [4]. This data could then either be used fully automatically, as often advocated in the machine learning and data mining literature, or with the human-in-the-loop, as primarily focused on in the visualization and human-computer interaction communities. Although a fully automatic solution is often desired for cost and time reasons, the AEC industry offers several characteristics (detailed in the next section) that call for human-in-the-loop solutions.

On the one hand, there is an inherent need for human judgment during the different phases of AEC. This holds, for example, during the design phase where the process has a creative and artistic sense to it, or during the fabrication and construction phases where some tasks are better done by humans than by machines or robots. Hence, the primary goal will be to support architects and craft workers with data-driven methods and respective interfaces to analyze the data and/or interact with machines or robots, rather than fully replace them with automatic solutions.

On the other hand, in contrast to other areas such as automotive manufacturing, the AEC industry is far from being completely formalized and standardized. The building industry faces requirements that differ with each building [5]. Additionally, the domain analysis tasks are not well-defined, and the domain knowledge is yet to be extracted and digitized. While this characteristic holds for many design study problems [4], it is rather amplified in the AEC industry, considering the breadth of domains involved, as a result of the co-design approach [6]. Moreover, in contrast to design workflows, digital data in construction and fabrication workflows are often missing, or of poor quality. All of that leads to ill-defined tasks and incomplete data [7].

Visualization research in a broader sense can help address this problem by providing human-in-the-loop solutions to support AEC practitioners during the design, fabrication, and construction workflows. These solutions could be application-driven research such as design studies to support analysis situations with ill-defined tasks and incomplete data, immersive-based ones to facilitate the communication between human (co-)workers and digitally controlled systems, or situated analytics to support on-site data analysis.

Our work provides the following contributions: First, we characterize the AEC industry with a particular focus on the next generation of digital buildings. Second, we describe possible challenges when designing and building AEC visualization solutions along with general strategies that could help approach these challenges. Third, we showcase several examples where we have already made progress toward visualization-enhanced AEC. And fourth, we report on general lessons learned that could help future research in AEC visualization and beyond.

This work is based on a long-term and large-scale collaboration between visualization and AR researchers and various domain experts in architecture, engineering, fabrication, and construction—in particular, in the context of the Cluster of Excellence on *Integrative Computational Design and Construction for Architecture (IntCDC)*[1] and the Collaborative Research Center on *Adaptive Skins and Structures for the Built Environment of Tomorrow*.[2]

AEC Characteristics

Based on our interdisciplinary collaboration with domain experts and mainly relying on the long-term experience of the domain experts and their integration with industrial practice, we would like to highlight a few characteristics of the AEC industry that have a connection to visualization.

Co-Design (or Breadth of Domains)

To address many of the challenges faced by the AEC sector, a co-design approach is em-

[1]https://www.intcdc.uni-stuttgart.de/
[2]https://www.sfb1244.uni-stuttgart.de/

(a) The Fiber Pavilion is entirely made out of carbon and glass-fiber composites. Each component was robotically fabricated using the coreless filament winding technique. ©ICD/ITKE University of Stuttgart.

(b) The Wood Pavilion spans 30 m over a flexible event space and is built from 376 bespoke hollow wood cassette segments. ©ICD/ITKE University of Stuttgart.

Figure 2: The Fiber Pavilion (a) and the Wood Pavilion (b) built by the University of Stuttgart (Institute for Computational Design and Construction and Institute of Building Structures and Structural Design) for the German National Garden Festival 2019 in Heilbronn, Germany, are great examples of how technological innovation can be translated into new architectural expressions. The lightweight and structurally efficient structure of the Fiber Pavilion is composed of 60 bespoke tubular fiber components forming a segmented dome spanning over 23 m. Aiming to create a public exhibition space, a floor area of around 400 square meters is formed by the glass and carbon fiber structure enclosed by a transparent membrane. This translucent skin highlights the material differentiation from components with less carbon fiber at the top toward denser material application on the components closer to the ground [8]. The Wood Pavilion demonstrates how computational design methods integrated with novel robotic fabrication processes allow a radical reinterpretation of structural wood tectonics and novel spatial qualities [9]. The segmented timber shell structure was built from hollow cassettes that leverage more intelligent material distribution within the structure and increase the system's structural performance by a factor of three while using the same amount of material per square meter. Such differentiated complexity nevertheless could only be achieved through advanced robotic fabrication modalities and integrated computational design models. Both projects integrate years of research in biomimetics, computational design methods, structural engineering, and a customized robotic fabrication leading to novel and genuinely digital building systems. The authentic architectural expression represents new ways of digital making and gives an idea of what the future of construction can look like.[3,4]

ployed [6] [9]. Such an approach involves many domains that stretch from architectural design to building materials and fabrication robotics and all the way to work processes with human labor on the construction site. Visualization research can play an important role by bridging the different domains. For example, it can bridge gaps between technical data representation (say, on robotic control) and its socio-technical context (such as human-centered work processes) by using visual communication and interaction.

Cyberphysical Systems

A general strategy for increased productivity and accuracy adopts the inclusion of more automatized fabrication, in particular, relying on flexible robotic systems [10]. This strategy is shared with many other industries, including manufacturing and Industry 4.0. However, the visualization community has not yet embraced cyberphysical systems to the extent required for AEC. For example, we often lack adequate visualization approaches to monitor and control production processes integrated with robotic systems. Also, there is little prior work on coupling physical systems with software (visualization) [11].

[3] https://www.icd.uni-stuttgart.de/
[4] https://www.itke.uni-stuttgart.de/

The Diversity or Lack of Data
Another characteristic of AEC is the diversity of the types of data involved. The data sources range from partly standardized data in Building Information Modeling (BIM), digital twins, proprietary CAD models, results from finite element simulations, process data from fabrication automatization, all the way to old legacy data from building authorities. However, data is not equally available or of the same quality across all AEC phases. For example, while data in digital formats is often available during the design phases, it is missing or of poor quality in the fabrication and construction phases.

Lack of Standardization
Dubois and Gadde [5] describe the construction industry as a loosely coupled system in which couplings among activities, resources, and actors are tight during individual projects, but the level of integration is loose during collective adaptation in the network across projects. Each building project is characterized by a unique set of boundary conditions such as building purpose, location, local regulations, and project stakeholders. Custom collaborative teams of planning and production entities are set up for each project to optimize the teams' ability to respond and manage these boundary conditions most effectively. Therefore, the collaborators typically rotate with each new project. This demands a level of flexibility from automation technologies that so far cannot be met with existing software and automation tools that are mostly set up for systems of scale. Although flexibilization and customization of standardized production have been gaining traction within the manufacturing industries such as Industry 4.0 or Smart Manufacturing [12], the majority of the developed tools and organizational systems are not directly transferable to the construction sector [13] as they are predominantly built around standardized systems, which only allow for limited product variety.

Creativity and Innovation
Creativity and innovation are prominent characteristics of the AEC industry. Not only because architecture is an inherently creative and artistic practice with a high sense of individuality. But also due to the grand challenges that the AEC sector faces, they are continuously pushing the industry toward coming up with new designs, experimenting with new building materials, or developing new methods for construction and fabrication. In such a creative environment, AEC practitioners have to rely on experience and intuition to navigate new and unfamiliar design spaces. This strategy might be sufficient to find successful solutions but not good enough to understand the new design spaces.

Sustainable Structures
Sustainable structures are characterized by the efficient use of resources and space, as well as the use of environmentally-friendly building materials. One common issue that the AEC industry faces nowadays is the overconsumption of building materials due to designing structures that maintain a very high safety factor. Such structures are built to handle peak loads that rarely—sometimes never—occur during the lifetime of a structure and are often oversized regarding the average load. This issue, however, reflects the lack of digital tools that could support AEC practitioners analyzing, monitoring, and predicting the behavior of the structures under varying typologies, geometries, loads, or building materials.

Building Demonstrators
Building demonstrators are the primary way of evaluation in the AEC industry. Figure 2 showcases two examples. Building demonstrators are examples of evaluation outside the lab, within a realistic environment with all it entails, from the required coordination with an extensive range of different domain experts to following regulatory and safety constraints. Therefore, they are a comprehensive way of capturing the complexity of *Co-design*. In contrast to AEC, it is especially uncommon to have evaluations of the complex interplay of visualization and its surrounding environment (i.e., understanding environments and work practices), as pointed out by Lam et al. [14]. While we see good use of the breadth of available evaluation methods within the visualization community[5], we want to highlight *Building Demonstrators* as an additional context for evaluation. The advantage of a building demonstrator is that it provides a great middle-ground between typical research prototypes (as often used in visualization

[5] https://beliv-workshop.github.io/

research) and fully transferring technology to daily industrial practice (which is rarely feasible for research results).

Visualization: Solutions and Challenges

As illustrated, several characteristics of the AEC industry such as *Cyberphysical Systems*, *Sustainable Structures*, and *Co-Design* can be viewed as solution strategies employed by the industry to increase its productivity and the quality of the building systems. These strategies, however, come short of realizing their potential due to the lack of digital tools to back and support them. We argue that visualization research is an essential instrument toward building and designing these tools.

There are essentially two components that support this argument: (1) the inherent need for human judgment in various stages of AEC, (2) the *Lack of Standardization* and/or the *Lack of Data*, leading to a wicked problem with ill-defined tasks and incomplete data [7]. Such a problem cannot be automatically solved using machine learning or data mining methods and rather calls for human-in-the-loop visualization solutions. These solutions may range from visual analytics systems for expert users like architects or robotic engineers to situated visualization linked to AR on the construction site, all the way to AR and human-robot interaction support for fabrication workers. Designing and building these solutions will come with new and interesting challenges:

Knowledge Discovery and Requirements Analysis

The knowledge discovery and requirements gathering and elicitation are lengthy and exhaustive phases. On the one hand, this is due to the many domains involved as a result of the *Co-Design* aspect. This requires visualization researchers and developers to communicate with very different domain experts and acquire knowledge from different backgrounds, including, for example, architecture, engineering, social sciences, industry stakeholders, and construction workers. On the other hand, it is due to the lack of understanding of the new design spaces among the domain experts themselves, as a result of the *Creativity and Innovation* aspect of AEC.

Flexibility and Customizability

Due to the *Co-Design* and *Lack of Standardization* aspects of AEC, visualization solutions need to consider different target users, workflows, levels of abstraction, different analysis tasks, all the way to different views and visualization types. Achieving such a degree of flexibility and customizability is not a trivial task and a well-known challenge in software engineering.

Data Integration

Data interoperability and integration are challenges in general. Visualization, in particular, has to be able to deal with this diversity of data, including visual integration of spatial and nonspatial (abstract) data, data-poor and data-rich inputs, temporal evolution, and varying data quality in the sense of uncertainty visualization.

AEC Ecosystem

Any digital solution has to fit into the already existing, quite complex ecosystem of AEC. In particular, it has to integrate with existing tools, workflows, processes, and the like. Therefore, any visualization contribution needs to provide interoperability with other ecosystem components, which is especially hard when sufficient speed and data access have to be guaranteed for interactive applications.

To address several of these challenges, we argue that user-centered design methods such as design studies [4], participatory design [15], or creativity workshops [16] are essential to build and design these solutions. Considering the *Co-Design* aspect, these solutions can serve as bridges between the various AEC domains. The current digitization approach in AEC is mostly restricted to establishing interoperability along the downstream direction of a pipeline from architectural design to fabrication and construction. We advocate boosting this integration by connecting the various components also in the upstream direction and with various links between the manifold technical components, processes, and stakeholders. In the following sections, we showcase three human-in-the-loop-based solutions that target different phases of AEC.

Example: Visualization for Coreless Filament Wound Structures

In this example, we explore the role of visualization in the design phase of coreless filament wound structures (CFWS). CFWS are examples of the next-generation building systems designed to address several of the key challenges facing the AEC industry. CFWS are made of fiber-reinforced polymers (FRP), a material characterized by a minimal self-weight and a high load-bearing capacity, making it widely used in fields like automotive, aeronautics, and ship-building. In the last decade, through the development of new robotic fabrication techniques such as coreless filament winding [17], it became feasible to use FRPs in full-scale architectural projects as well (see Figure 2).

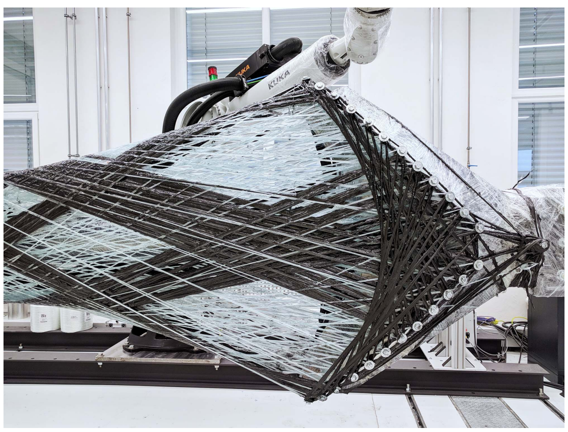

Figure 3: Coreless Filament Wound Structures (CFWS) are formed by a systematic sequence of fiber placement within defined boundary conditions. ©ICD/ITKE University of Stuttgart

CFWS are formed by a systematic sequence of fiber placement within defined boundary conditions (see Figure 3). Their structural performance relies on fiber interactions, that is when fibers are pressing against each other, to ensure the necessary tension in the system [17]. By varying the input parameters (i.e., boundary conditions and/or the winding sequence), different geometrical solutions can be obtained. However, these solutions have to satisfy both functional and aesthetic criteria. While some of these criteria can be numerically calculated, others (like aesthetics) are hard to quantify. Additionally, there is little understanding of how the input parameters interact with each other and how they influence the functional and aesthetic criteria. Therefore, an in-depth exploration of CFWS is required to better understand the design space and arrive at a valid fiber sequence. To enable that, simulation and optimization methods are used to generate large varieties of CFWS, while visualization is used to aid the exploration and analysis.

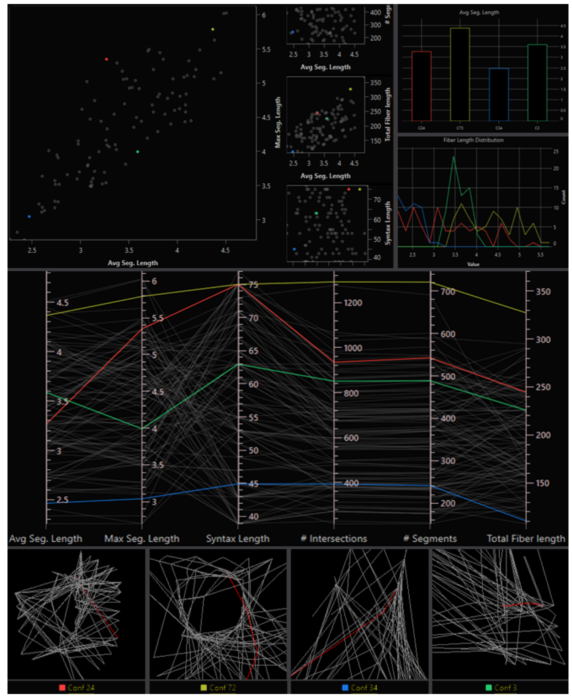

Figure 4: Examples of visualizations implemented to support the analysis and exploration of CFWS at different levels of detail.

In our work, we aim to design a visualization tool to support the exploration and analysis of the simulation results at various levels of detail. These levels are meant to support the different analysis tasks requested by the designers. For example, on the overview, designers want to identify clusters of solutions or correlations between the attributes of CFWS. In contrast, on a detailed level, designers want to examine single solutions. That is, to spot the loose fibers, identify kinks, or examine the overall distribution of intersections across the structure. To go from the overview to the detailed view, designers often need to select and filter the overview to only a few candidate solutions and compare these solutions based on quantitative or qualitative (i.e., aesthetics) criteria. Figure 4 shows some of the visualizations we implemented to support these tasks. While parallel coordinates plots and scatter plot matrices provide an overview of the solution space, small multiples representations together with the line- and column-chart enable the comparison between the candidate solutions.

This tool prototype can serve as an early manifestation of visualization and visual analytics opportunities in the CFWS domain. While the tool does not introduce a novel visualization technique per se, we argue that the value of our work lies in understanding and characterizing the CFWS domain, which is a challenging task given the *Breadth of Domains* involved and the *Creativity and Innovation* aspect. The tool is implemented using C# and Windows Presentation Foundation (WPF) with the help of the SciChart library[6]. This allows for smooth integration with the Grasshopper plugin for Rhino, which is a central part of the architecture software ecosystem.

Example: AR for Human-Robot Collaboration

AR technology is gaining traction within the AEC field. The concept of complementing the real world with a digital representation of otherwise not visible data has opened a new path for a great variety of applications [18]. In this example, we investigate the concept AR-based human-robot collaboration (HRC). AR-based HRC aims to integrate human labor and industrial robots in a collaborative fabrication environment through the use of AR technology. Such integration promises a smarter, more flexible, and intuitive manufacturing process, resulting in a skill set extension of the whole fabrication setup.

A central approach is to share tasks between humans and robots as individual but collaborative fabrication units regarding their skill set. For example, the robot picks up a timber slat and holds it in place, while a human fixes it with screws [19]. Due to safety precautions, this kind of human-robot collaboration is limited, especially in a shared workspace, and requires the use of specialized low-payload collaborative robots with additional sensors, so-called *cobots*. Additionally, the fabrication sequence has to be predefined, which leaves no room for adjustments during the fabrication workflow.

[6]https://www.scichart.com/

In our current research, we investigate the concept of instructive human-robot collaboration. Building upon AR-based HRC, we introduce a new communication layer between these two fabrication units. This concept aims to hand over the control of the fabrication workflow to the craft workers. To that end, we developed a computational framework that provides an easy-to-use interface between a human and a 14-axes robotic fabrication setup via a Microsoft HoloLens head-mounted display (HMD).

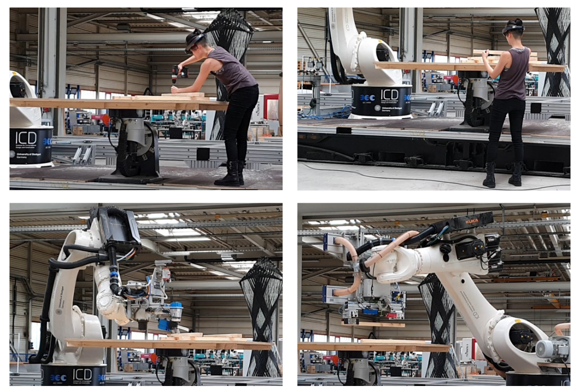

Figure 5: The human and the robot are fixing the timber slats into position using different tools.

To showcase the instructive HRC concept, we developed a simple fabrication routine where an AR-equipped human and the robotic fabrication setup are collaboratively assembling a timber structure for a trade show stand. To fix the timber slats into positions, the robot uses a wood nail gun while the human uses a cordless screwdriver (see Figure 5). While the robots could solely execute this routine, there are potential sources of failures considering the material and the non-repetitive fabrication of one-off components. Therefore, the fabrication routine benefits from a collaborative effort between human and robots. The use of HMDs allows the workers to have their hands free to perform the tasks while having real-time access to all the necessary information as shown in Figure 6. This interface enables the craft workers to give direct instructions to the robots, coordinating and re-arranging the fabrication process on the fly. Additionally, it does not require any technical background, just knowledge of the workflow.

This example shows how AR-based visualization can help advance *Cyberphysical Systems* during fabrication and construction. We argue that the extension of human crafting skills with the possibility to coordinate or take over specific tasks of an automated fabrication workflow could substantially increase the flexibility and robustness of highly automated (pre-)fabrication setups. This extension is particularly relevant within the project-based construction industry, where efficient and flexible production of one-off components is predominant. For a successful implementation of such a concept in prefabrication, several key challenges arise. In particular, purely inside-out tracking-based principles are prone to interference and HMDs are still too heavy and distracting for safe use in the dynamic and hazardous environment of fabrication lines or even construction sites. In addition, the development of visual user interfaces that can be learned, understood, and controlled quickly and safely by untrained persons will also play an important role in the acceptance and the use of these technological innovations.

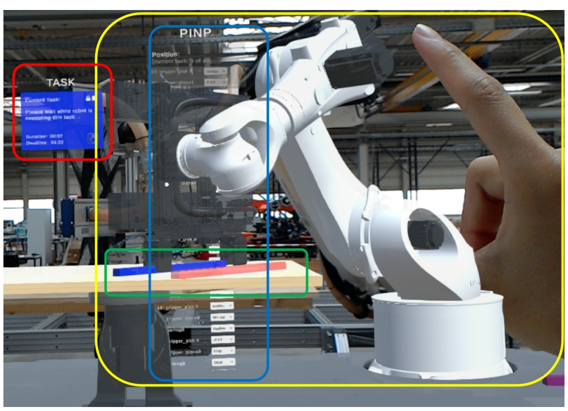

Figure 6: The HMD inside view shows all the necessary information about the fabrication task under execution. The relevant pieces of information are highlighted by drawing colored frames around them: The task window (□), the task list (□), the digital twins of the robots (□), and the work object (□).

Figure 7: Rendering of actuators that are integrated into a building's support structure to compensate for the stress caused by rare, high loads.

Example: Situated Visualization of Adaptive Structures and Skins

In this final application example, we explore the role of situated visualization for adaptive buildings. A promising approach to produce more *Sustainable Structures* is the introduction of adaptivity into buildings. Using a tightly coupled setup of sensors, controllers, and actuators that are integrated into the building (see Figure 7), it becomes possible to build more lightweight structures with significant savings of material, as the actuators can temporarily compensate for the stresses caused by rare, high loads. Adaptivity can be also applied to skins, where it enables a building to dynamically react to changing conditions including climate and lighting. The primary focus of our concept for situated visualization is to monitor the state of an adaptive building during its operation and to provide visual analysis of available data on-site. The advantage over traditional monitoring equipment and off-site visual analysis sessions is that the visualizations can be viewed at the same time as the actual real-world components and that the spatial context of the real world is retained.

For simple monitoring scenarios, raw data values are displayed in real-time directly at the spatial locations of the sensors that produced them. An example is shown in Figure 8: Forces measured by sensors on a scale model of an adaptive high-rise building are displayed both as numerical values at each of the elements respectively and by coloring selected elements, when

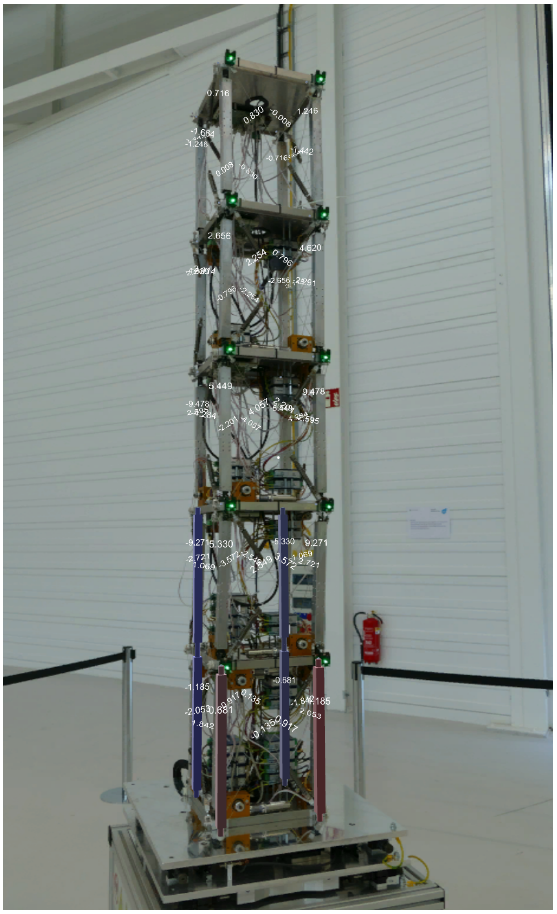

Figure 8: A scale model of an adaptive high-rise building with AR overlay. Forces are displayed both as numerical values and for selected struts (in the first and second segment from the bottom) by coloring.

viewing the scale model through an AR-headset. More complex live monitoring scenarios include displaying higher-level information, for example, the expected remaining lifetime of individual components in the building, or showing discrete event-driven data to inform users about critical events such as a failure of one of the actuators in the building. By processing the raw data and taking historical data into account, situated visualization allows architects, civil engineers, and researchers from other domains to gain insights into the evolution of the building, inspect past events, and ideally predict future states.

There are, however, several challenges that arise when developing AR-based situated visualizations for use in an actual *Building Demonstrator*. First, the sensors distributed throughout an adaptive building continuously provide data at high refresh rates. For live monitoring, this data needs to be processed by the visualizations at high frame rates and with low latency. Another challenge is obtaining a consistent and robust registration of the virtual scene and the real world. A basic approach is to place fiducial markers in the real world that can be automatically detected by a built-in camera of the AR device and used to establish a common frame of reference. More advanced approaches include matching the detected scene to a given virtual model to automatically infer the user's location. The display technologies currently used also pose limitations with respect to the field of view (approx. $55°$ for Microsoft HoloLens2), and thus the available display space for visualizations is limited to the available display resolution. Another challenge is the limited display brightness in the context of bright daylight.

Another important aspect to consider is the diverse user types for the situated visualizations. While the primary users are the domain scientists from the complete *Breadth of Domains* in AEC, in the future, residents are also expected to have an interest in understanding and being informed about the state of the building they inhabit. Therefore, visualizations need to be *Flexible and Customizable* enough to visually represent the data at various level of detail. While domain experts require access to all of the available data and also the capabilities to interpret it, layman users require a much simpler representation of the data that provides a fast and easy-to-understand overview.

Discussion

We now reflect on the experiences that we have had with our collaborative research in AEC.

Opportunities for Future Visualization Research We see AEC as a highly relevant application area that, from our perspective, has not been considered enough by the visualization community. There is plenty of previous work on visual support for architectural design and planning. In fact, computer-aided design and visualizations of building plans for virtual walk-throughs were embraced very early on. However, the link between visualization research and the other stages of AEC, particularly regarding the fabrication and construction processes, is largely missing. One of the few prior works that target construction is by Ivson et al. [20]. However, there is much need for other aspects of AEC, and especially for visualization that supports an integrative and *Co-Design* approach. We see the value of AEC visualization in both directions: Visualization can contribute its share to addressing big global issues related to population growth, sustainability, and climate change. And, conversely, the diversity of requirements from AEC serves as rich input for driving future visualization research. For example, we see potential pushes in the direction of situated visual analytics/AR, or uncertainty-aware visualization that integrates various spatial and non-spatial data sources.

Lessons Learned

Much of our collaborative and interdisciplinary work has been rooted in following the design study approach—with all its typical advantages and caveats [4]. However, we have seen the additional challenges and benefits that come from working not just with one group of domain experts but with teams that cover a large range of backgrounds, domains, and expertise. In our case, domains span from architecture, structural engineering, and building physics all the way to engineering geodesy, manufacturing, system engineering, robotics, and social sciences—all linked to industry partners and applications. This setup makes communication and coordination even harder than for more bilaterally-structured application-oriented visualization work, but it comes with the great advantage that rather comprehensive problems can be tackled.

Another lesson learned is the value of *Building Demonstrators*. They provide a valuable bridge between typical research-oriented application work, including many of the typical design study papers, and completely industry-driven development that is often restricted to transferring knowledge from research to products. Building demonstrators provide an instrument that includes the important components for ecological validity but still permits research orientation and experimentation. It is open for discussion whether similar kinds of demonstrators can be established for other visualization-related application areas.

CONCLUSION

We have discussed the general motivation, characteristics, and challenges that come with a digital transformation of architecture, engineering, and construction—along with the specific role that visualization plays here. Some concrete examples have showcased the potential use of visualization for the future building industry. Overall, we see great opportunities for visualization research in this application area.

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